An Upper Mass Bound of a Two-Component Protogalaxy

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Abstract

We investigate the physical properties of a two-component virialized protogalaxy comprising a hot gas and cold clouds which are in pressure equilibrium under the assumptions that the protogalaxy is both spherical and homogeneous. Two conditions which we adopt are that the protogalaxy is in virial equilibrium and that the cooling time is less than the dynamical time. It is found that there exists an upper mass bound for such a two-component protogalaxy when the cloud mass is comparable to or greater than that of hot gas. We also consider the stability of the cold cloud against the Jeans instability and Kelvin-Helmholtz instability.

Key words : Galaxies: evolution—Galaxies: halo—Galaxies: ISM

1. Introduction

Recently, a remarkable series of observations has revealed many high-redshift galaxies, radio sources, and quasars to the redshifts greater than four, thus suggesting important implications about galaxy formation and evolution (McCarthy 1993). Theoretically, from the 1980s many large simulations concerning galaxy formation in the context of large-scale structure

formation have been performed (e.g. Efstatiou, Silk 1983; Cen, Ostriker 1992 and references there in). Since there still remain many uncertain processes in galaxy formation, it could be valuable to clarify the fundamental nature of galaxy formation by a simple analytic treatment.

A few decades ago several attempts were proposed (Ostriker 1974, talk at 7th Texas Conference; Gott, Thuan 1976; Rees, Ostriker 1977; Silk 1977; Rees 1978). In these studies, it was proposed that a protogalaxy consists of one component homogeneous gas in a virial equilibrium state; it was assumed that radiative cooling controls the fate of the protogalaxy, with the ratio of cooling time to the collapse time being a controlling parameter. Their conclusions are that if free-free cooling dominates over bound-free cooling, the upper bound to the radius of a protogalaxy can be uniquely expressed by only fundamental constants, and that if bound-free cooling predominates, its mass is uniquely expressed as well.

On the othe hand, another model was proposed in which the protogalaxy comprises a hot gas and cold clouds (Fall, Rees 1985) because the hot gas component is thermally unstable to make cold clouds with mass around globular clusters. Regarding such a two-component model of a protogalaxy, Ikeuchi and Norman (1991) examined the equilibrium structure, and obtained the expressions of its physical quantities by using fundamental constants and several additional parameters. Recently, Mathews and Schramn (1993) and Lee et al. (1994) have studied the star-formation history of a two-component galactic halo within the expanding background universe. They emphasized that in order to explain the age discrepancy in the galaxy two different types of star-formation modes are required. One is such an efficient star-formation as induced by cloud-cloud collisions in the halo; the other is the quiescent star-formation in the disk.

In this paper we consider the physical properties of a two-component virialized protogalaxy by a simple analysis, and give an upper mass bound for it when the cloud mass dominates over the hot gas mass. We also consider the stability of cold clouds against the Jeans instability and Kelvin-Helmholtz instability.

2. An Upper Mass Bound

2.1. Basic Equations and Assumptions

Following the discussion by Ikeuchi and Norman (1991), we assume for simplicity that this two-component protogalaxy is spherical and homogeneous. Suppose that $N_{\rm c}$ cold clouds of each radius $R_{\rm c}$, mass $M_{\rm c}$, and temperature $T_{\rm c}$ are embedded in a hot gas of radius $R_{\rm h}$, mass $M_{\rm h}$, and temperature $T_{\rm h}$. To determine the physical properties of this two-component protogalaxy, seven equations, or reasonable assumptions for seven quantities in the above, are needed. They are as follows:

(i) Virial equilibrium,

$$\sigma_{\rm v}^2 \quad = \quad 0.6\frac{G(M_{\rm h}+N_{\rm c}M_{\rm c)}}{R_{\rm h}} = 3\frac{kT_{\rm h}}{\mu_{\rm h}m_{\rm p}}, \tag{1}$$

where $\sigma_{\rm v}(T_{\rm h}), \mu_{\rm h}$, and $m_{\rm p}$ are the virial velocity of protogalaxy, the mean molecular weight of hot ambient gas, and the proton mass, respectively. For a primordial wholly ionized gas, $\mu_{\rm h} = 0.609$. We do not explicitly include the gravity of dark matter in this paper.

(ii) Equality of the free-fall time and cooling time ($\tau_{\rm ff} = \tau_{\rm cool}$),

$$\sqrt{\frac{3\pi}{32}}\sqrt{\frac{c_{\rm v}R_{\rm h}^3}{G(M_{\rm h}+N_{\rm c}M_{\rm c)}}} \quad = \quad 1.5kT_{\rm h}\frac{c_{\rm v}(R_{\rm h}^3-N_{\rm c}R_{\rm c}^3)\mu_{\rm h}m_{\rm p}}{M_{\rm h}c_\Lambda\Lambda(T_{\rm h})}, \tag{2}$$

where $c_{\rm v} = 4\pi/3$ is a volume element, $\Lambda(T_{\rm h})$ is the cooling function of a primordial gas in units of erg s^{-1} cm^3 (Binney, Tremaine 1987) and $c_\Lambda = 0.821$ is a correction factor to the fitting formulae for the cooling function. Strictly speaking, the protogalaxy will collapse when the condition $\tau_{\rm ff} > \tau_{\rm cool}$ is satisfied. We should thus note that equation (2) gives the maximum mass/minimum radius of a collapsing protogalaxy. If the luminous mass of the galaxy is condensed in the dark halo (White, Rees 1978), we must consider a vast amount of dark matter. A zeroth-order incorporation of this effect can be achieved by changing the gravitational constant G to G[1+$M_{\rm d}/M_{\rm b}$] in equations (1) and (2), where $M_{\rm d}$ and $M_{\rm b}$ are the

masses of the dark matter and baryonic matter, respectively.

(iii) Pressure equilibrium between clouds and hot ambient gas,

$$\frac{\rho_{\rm h}}{\mu_{\rm h} m_{\rm p}} T_{\rm h} = \frac{\rho_{\rm c}}{\mu_{\rm c} m_{\rm p}} T_{\rm c}, \tag{3}$$

where $\mu_{\rm c}$ is the mean molecular weight of the gas in cold clouds of primordial abundance, $\mu_{\rm c}$ =1.23.

(iv) Energy balance condition,

$$n_{\rm h}^2 c_\Lambda^2 \Lambda(T_{\rm h}) c_{\rm v} (R_{\rm h}^3 - N_{\rm c} R_{\rm c}^3) = \frac{N_{\rm c}}{c_{\rm v} R_{\rm h}^3} \pi R_{\rm c}^2 \sigma_{\rm v} \eta (N_{\rm c} M_{\rm c} c^2). \tag{4}$$

Here, we assume that the energy loss from the hot region is supplied by the energy liberation by the cloud-cloud collisions, and η denotes the fraction of the liberated energy to the cloud rest mass. In the following, we suppose that $\eta \approx 10^{-5}$—10^{-6}. These values are the observed ones in molecular clouds, considering that the mass fraction of energy liberation from newly born stars is $\sim 10^{-3}$, and the star-formation efficiency from clouds is in the order of 10^{-2}—10^{-3}. We suppose that this cloud-cloud collision induces efficient star-formation during an early stage of protogalactic evolution. For our model to be consistent, the cold clouds must be stable (discussed in section 3).

Conditions (i)—(iv) are the physical assumptions for a two-phase system. To determine seven quantities, we need to specify additional three conditions, though we do not have appropriate ones at present. We regard the three quantities $T_{\rm h}, T_{\rm c}$ and $F_{\rm v}$ as being free parameters, where $F_{\rm v}$ is the volume-filling factor of clouds,

$$F_{\rm v} = \frac{N_{\rm c} R_{\rm c}^3}{R_{\rm h}^3}. \tag{5}$$

Using the characteristics of the cooling function of primordial gas, we suppose that the hot gas temperature $T_{\rm h}$ is $> 10^{6.26}$K, in which the hot gas is thermally stable, and that the cold clouds temperature $T_{\rm c}$ is 10^4K, in which the primordial cooling function has a sharp cut-off,

because of recombination to hydrogen atoms. A more detailed discussion concernig the cloud temperature is given by Kang et al. (1990).

By using the above four equations (1)—(4) with three free parameters $F_{\rm v}, T_{\rm c}$, and $T_{\rm h}$, we can obtain the equilibrium masses and radii of the hot region and cold clouds as follows:

$$R_{\rm h} = 0.416 \frac{1}{f} \times \frac{\Lambda(T_{\rm h})}{G(kT_{\rm h})^{0.5} m_{\rm p}^{1.5}}, \tag{6}$$

$$M_{\rm h} = 3.41 \frac{(1-F_{\rm v})}{f^2} \times \frac{\Lambda(T_{\rm h})(kT_{\rm h})^{0.5}}{G^2 m_{\rm p}^{2.5}}, \tag{7}$$

$$R_{\rm c} = 0.440 \frac{F_{\rm v}^2}{f(1-F_{\rm v})} \times \frac{\Lambda(T_{\rm h})(\eta c^2)}{G m_{\rm p}^{0.5} k^{1.5} T_{\rm h}^{0.5} T_{\rm c}}, \tag{8}$$

$$M_{\rm c} = 8.17 \frac{F_{\rm v}^6}{f^2(1-F_{\rm v})^3} \times \frac{m_{\rm p}^{0.5} \Lambda(T_{\rm h}) T_{\rm h}^{1.5} (\eta c^2)^3}{G^2 k^{2.5} T_{\rm c}^4}, \tag{9}$$

where

$$f = (1-F_{\rm v}) + 2.02 F_{\rm v} \frac{T_{\rm h}}{T_{\rm c}}. \tag{10}$$

2.2. Results

In figure 1, we show the relation between the total mass $M_{\rm total}(= M_{\rm h} + N_{\rm c} M_{\rm c})$ and the radius $R_{\rm h}$ of a two-phase protogalaxy for $T_{\rm c} = 10^4$ K, $\eta = 10^{-6}$, and five cases of $F_{\rm v}$. For a comparison, we plot the case of a one-component protogalaxy by a dashed line. As is well-known, in the case of a one-component protogalaxy (no clouds) the upper bound of the radius is obtained at the free-free cooling region. On the other hand, in the case of a two-component protogalaxy the total mass is limited lower with increasing the cloud fraction. For example, the total mass is bounded to $10^{13} M_\odot$ for $F_{\rm v} = 10^{-3}$. For this result, we can give a clear physical interpretation. The cooling time is determined by the hot gas, while the dynamical time is controlled by clouds for a cloud-dominant galaxy. That is, in a cloud-dominant galaxy the protogalaxy, itself, cannot collapse, because of an inefficient energy loss from the hot region

[see equation (2)]. The upper mass bound which we derived here is about two orders larger than the typical mass of a galaxy, $\sim 10^{11} M_{\odot}$. We discuss this point in section 4.

3.Stability of Clouds

In this two-component model, we assume that cold clouds collide with each other and liberate energy to the hot ambient medium. In order for this assumption to be satisfied, the cold clouds embedded in the hot medium must be dynamically stable. Therefore, we pose two stability conditions concerning the clouds.

3.1. Gravitational Instability

First, clouds must be gravitationally stable,

$$M_c \leq M_{\mathrm{c,Jeans,p}}, \tag{11}$$

where the Jeans mass of a pressure-confined cloud, $M_{\mathrm{c,Jeans,p}}$, is given by (Spitzer 1978),

$$M_{\mathrm{Jeans,p}} = 1.8 \frac{c_{\mathrm{c}}^4}{G^{1.5} P_{\mathrm{h}}^{0.5}}. \tag{12}$$

Here, c_{c} and P_{h} are the sound speed in the cloud and the pressure of the ambient hot medium, respectively. We apply (12) to the cold cloud,

$$M_{\mathrm{c,Jeans,p}} = 1.38 \times 10^7 \times \sqrt{1 - F_{\mathrm{v}}} (\frac{T_{\mathrm{c}}}{10^4 \mathrm{K}})^2 (\frac{10^6 \mathrm{K}}{T_{\mathrm{h}}})^{0.5} (\frac{R_{\mathrm{h}}}{100 \ \mathrm{kpc}})^{1.5} \sqrt{\frac{10^{13} M_{\odot}}{M_{\mathrm{h}}}} \quad M_{\odot}. \tag{13}$$

This mass is roughly comparable to the mass of a globular cluster (Fall, Rees 1985). Of course, if we take $T_{\mathrm{c}} = 10^2$ K, due to H_2 cooling (see Kang et al. 1990), this situation greatly changes. In this case, according to equation (13), the Jeans mass of a cold cloud is smaller by four orders of magnitude than that for the case $T_{\mathrm{c}} = 10^4$ K.

3.2. Kelvin-Helmholtz Instability

Second, clouds must be stable against the Kelvin-Helmholtz instability (Chandrasekhar 1961; Murray et al. 1992). This instability occurs when two media having different densities

are in relative motion. In the present situation, clouds with a density $\rho_{\rm c} \gg \rho_{\rm h}$ move in the hot medium with random velocity $\sigma_{\rm v}$. This instability occur when the momentum from a cloud to hot gas is transferred (cf. Chandrasekhar 1961), i.e.,

$$2\rho_{\rm c} R_{\rm c} \quad \geq \quad \rho_{\rm h} R_{\rm h}. \tag{14}$$

In another description, it reduces to

$$\begin{aligned} R_{\rm c} \quad &\geq \quad R_{\rm c,crit} = \frac{1}{2}\frac{\rho_{\rm h}}{\rho_{\rm c}} R_{\rm h} = 0.248 \frac{T_{\rm c}}{T_{\rm h}} R_{\rm h} \\ &= \quad 2.48 \times 10^2 (\frac{T_{\rm c}}{10^4 \text{ K}})(\frac{10^6 \text{ K}}{T_{\rm h}}) \sqrt{\frac{R_{\rm h}}{100 \text{ kpc}}} \quad \text{pc}. \end{aligned} \tag{15}$$

Since in this paper we assume that the cold clouds are confined by the pressure of the hot ambient medium, the stabilizing mechanism against the Kelvin-Helmholz instability, such as the self-gravity and magnetic field of the cold cloud, can be neglected, and the above simple treatment for the clouds is not sufficient. However, this is the most generous criterion. We call equations (11) and (15) the stability conditions, and $M_{\rm c,Jeans,p}$ and $R_{\rm c,crit}$ the critical mass and radius for the cold clouds, respectively.

3.3.Results

In figure 2a, we show the mass of a cold cloud as a function of the hot gas temperature $T_{\rm h}$ for $T_{\rm c} = 10^4$ K, $\eta = 10^{-6}$ and five cases of $F_{\rm v}$. The solid and dashed lines show $M_{\rm c}$ and $M_{\rm c,Jeans,p}$, which are calculated from equations (9) and (13), respectively. In figure 2b, we show the radius of the cold cloud as a function of the hot gas temperature for the same parameters as in figure 2a. The solid and dashed lines show $R_{\rm c}$ and $R_{\rm c,crit}$, which are calculated from equations (8) and (15), respectively. For different $F_{\rm v}$, $M_{\rm c,Jeans,p}$ and $R_{\rm c,crit}$ change only slightly while $M_{\rm c}$ sensitively changes. The gravitational stability condition gives the upper limit of the cloud mass (or $T_{\rm h}$), and the Kelvin-Helmholtz stability condition gives the lower limit of the cloud radius (or $T_{\rm h}$). As can be seen in figure 2, there are only small allowed regions of parameters for each $F_{\rm v}$. Table 1 summerizes the allowed ranges of $T_{\rm h}$ for each model, and

table 2 gives the physical quantities of a two-component protogalaxy when the median value of $T_{\rm h}$ from table 1 is taken for each model. In our model, the cold clouds of mass $\sim 10^6 M_\odot$ are confined by the thermal pressure of a hot ambient gas of mass $\sim 10^{13} M_\odot$, irrespective of $F_{\rm v}$.

4.Summary and Discussion

We considered the physical properties of a two-component protogalaxy by using a simple analytic treatment, and determined them considering the stability of the cold clouds. In the cloud-dominant protogalaxy, the mass of a protogalaxy is almost constant in the free-free cooling region above $\sim 10^6$ K. This means that a protogalaxy heavier than $\sim 10^{13} M_\odot$ cannot collapse. In contrast, the mass of an one-component protogalaxy is not limited. The stability condition for cold clouds against the Jeans instability and Kelvin -Helmholtz instability poses stringent limitations on the physical quantities of the two-component protogalaxy.

In our simple model, several important factors are neglected concerning the formation of galaxies, such as the abundance and distribution of dark matter (White, Rees 1978), the cosmological initial conditions, the effect of shock heating (Thoul, Weinberg 1995), the angular momentum and the deviation from spherical symmetry of a protogalaxy (De Araujo, Opher 1994). To explain the typical mass of a galaxy ($\sim 10^{11} M_\odot$), quantitatively, we must take into account the above-mentioned factors. The upper mass bound which we present here may give one possibility for the origin of the typical galaxy mass.

According to the present viewpoint of a two-component protogalaxy, we speculate on the star-formation history as follows. In the protogalaxy with radius $R_{\rm h} \sim 100$ kpc and a total mass of $M_{\rm total} \sim 10^{13} M_\odot$, the star-formation in an extended halo is triggered by cloud-cloud collisions and/or the shock compression of clouds by the jet suggested in high-redshift radio galaxies (McCarthy 1993; Norman, Ikeuchi 1994, private communication). These Population II stars distribute over the extended halo, and their low mass ends may be candidates for

MACHOs. Meanwhile, the hot gas is cooled and contracts to a disk or spheroid, depending upon its angular momentum. From this gas component, Population I stars are formed.

In the succeeding work we consider the evolution of this two-component protogalaxy. Especially, once the protogalaxy begins to collapse, the hot gas phase is cooled and contracts, while the cold clouds can not contract, because their random energy can not be extracted. That is, the hot gas and cold clouds segregate. At this stage the stability of the cold clouds changes, because of the lack of hot ambient gas. Including these processes, we examine the evolution of two-component protogalaxies.

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References

Binney J., Tremaine S. 1987, Galactic Dynamics (Princeton University Press, Princeton)

Chandrasekhar S. 1961, Hydrodynamic and Hydromagnetic Stability (Clarendon Press, Oxford).

Cen R., Ostriker J.P. 1993, ApJ 417, 404

De Araujo J.C.N., Opher R. 1994, ApJ 437, 556

Efstathiou G., Silk J. 1983, Fund. Cosmic Phys. 9, 1

Fall S.M., Rees M.J. 1985, ApJ 298, 18

Gott J.R.III, Thuan T.X. 1976, ApJ 204, 649

Ikeuchi S., Norman C.A. 1991, ApJ 375, 479

Kang H., Shapiro P.R., Fall S.M., Rees M.J. 1990, ApJ 363, 488

Lee S., Schramm D.N., Mathews G.J. 1995, ApJ 449, 616

McCarthy P.J. 1993, ARA&A 31, 639

Mathews G.J., Schramm D.N. 1993, ApJ 404,468

Murray S.D., White S.D.M., Blondin J,M., Lin D.N.C. 1993, ApJ 407, 588

Ostriker J.P. 1974, talk at 7th Texas Conference

Rees M.J., Ostriker J.P. 1977, MNRAS 179, 541

Rees M.J. 1978, Phys.Scripta 17, 371

Silk J. 1977, ApJ 211, 638

Spitzer L.Jr. 1978, Physical Processes in the Interstellar Medium (Wiley Interscience, New York).

Thoul A.N., Weinberg D.H. 1995, ApJ 442, 480

White S.D.M., Rees M.J. 1978, MNRAS 183, 341

Table 1. Allowed values for four parameters with respect to the Jeans and Kelvin-Helmholtz instability.

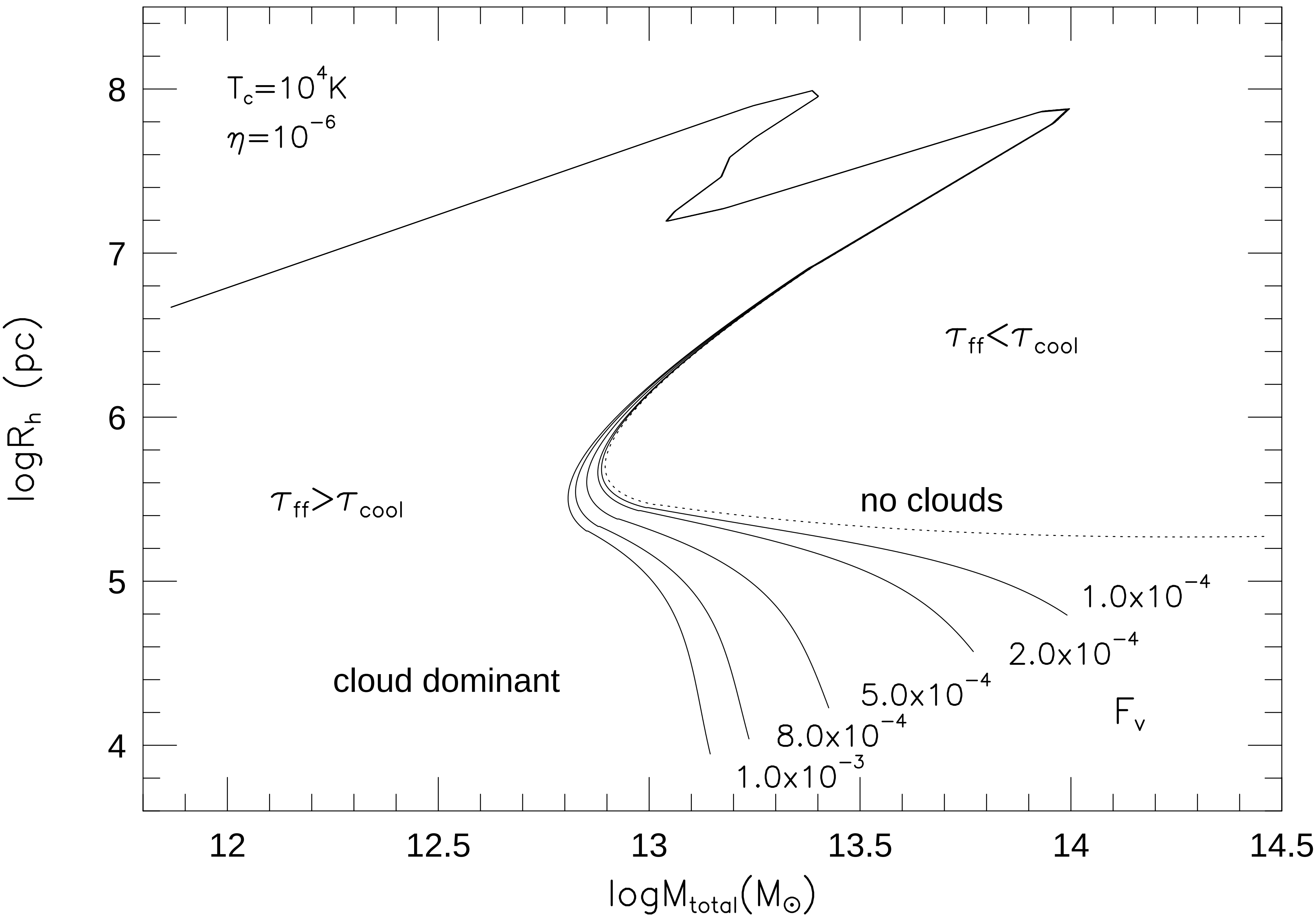
Model	$\log T_{\rm c}$	$\log \eta (10^{-6})$	$F_{\rm v}(10^{-4})$	$\log T_{\rm h}$(K)(allowed)
1	4	10	3.0	6.38—6.41
2			2.0	6.73—6.78
3			1.0	7.33—7.40
4		1	10.0	6.34—6.42
5			8.0	6.53—6.64
6			5.0	6.94—7.12

Table 2. Physical quantities of a two-phase protogalaxy for the median value of $T_{\rm h}$ in table 1.

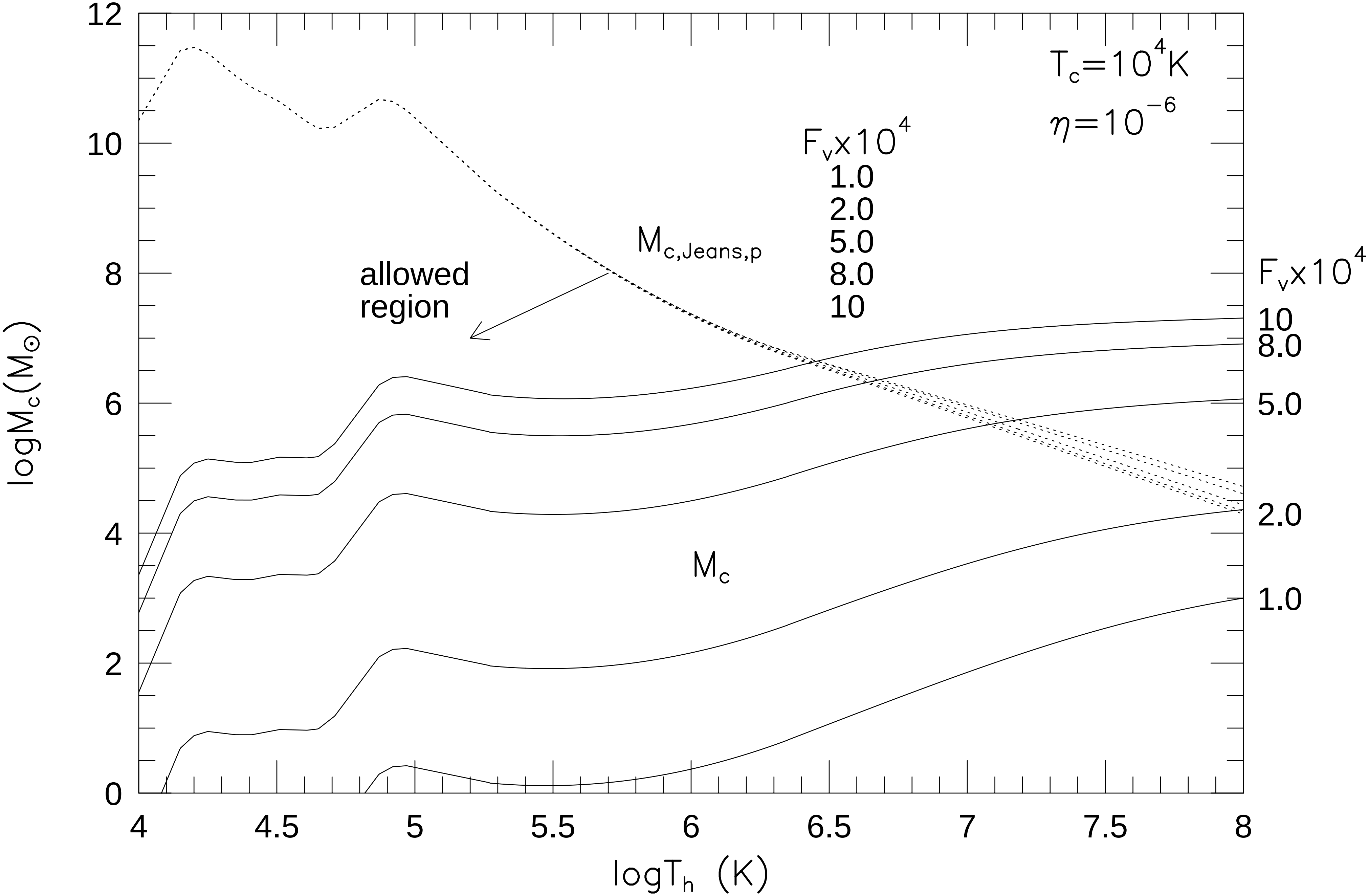
Model	$\log T_{\rm h}$(K)	$\log R_{\rm h}$(pc)	$\log M_{\rm h}(M_{\odot})$	$\log R_{\rm c}$(pc)	$\log M_{\rm c}(M_{\odot})$
1	6.40	5.39	12.93	2.41	6.68
2	6.74	5.29	13.14	1.95	6.18
3	7.36	5.13	13.51	1.18	5.37
4	6.40	5.28	12.70	2.34	6.59
5	6.60	5.19	12.77	2.06	6.28
6	7.00	5.03	12.92	1.49	5.60

Figure Captions

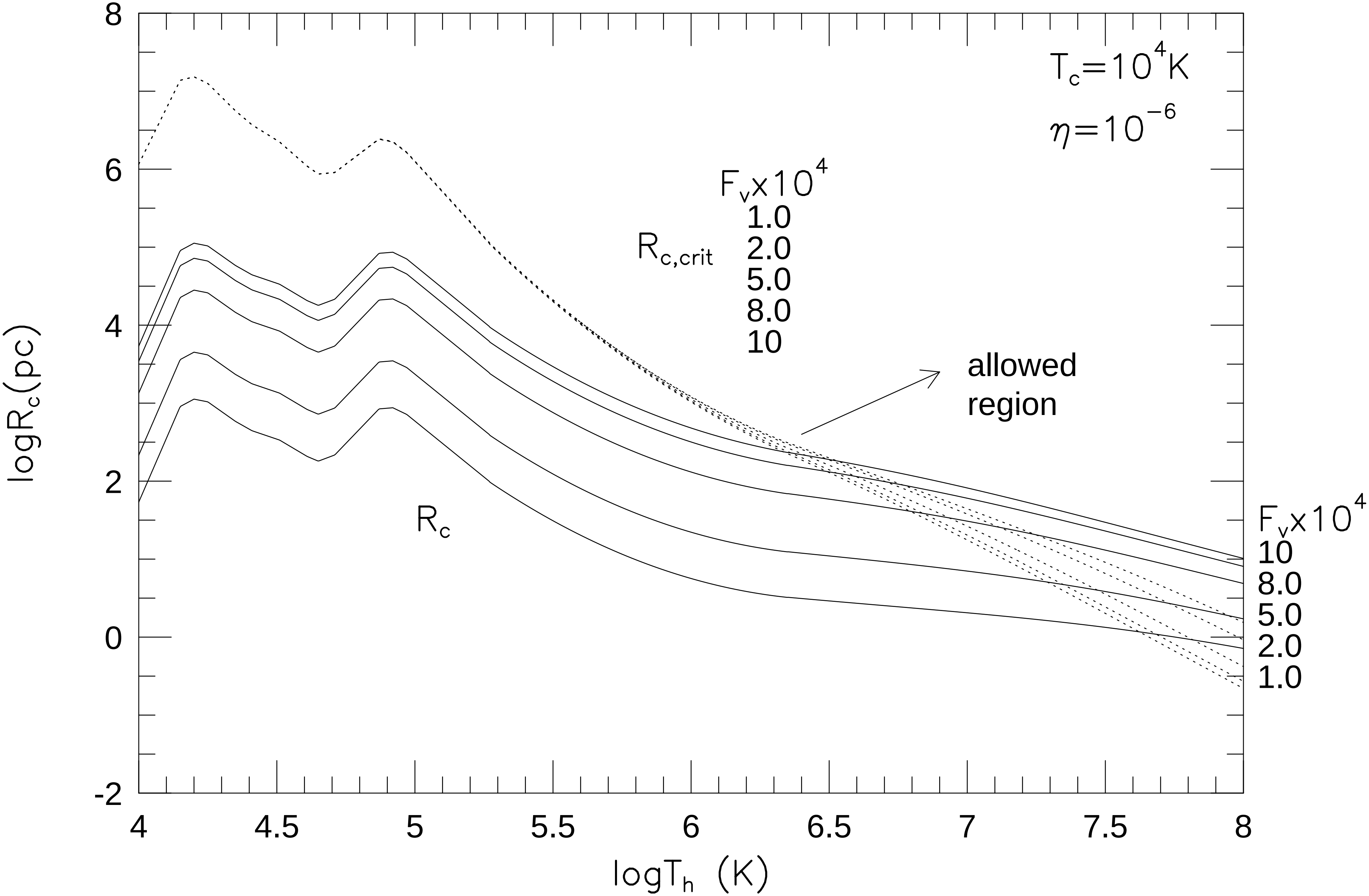
Fig. 1
Relation between the total mass and radius of a two-component protogalaxy for $T_\mathrm{c} = 10^4$ K, $\eta = 10^{-6}$ and five cases of F_v. For a comparison, the case without clouds is also plotted by a dashed line.
Fig. 2
Cloud mass (a) and radius (b) as a function of T_h for $T_\mathrm{c} = 10^4$ K, $\eta = 10^{-6}$ and five cases of F_v. The Jeans upper mass limit and the Kelvin-Helmholtz lower radius limit are illustrated by dashed lines for the same parameters.



$T_c=10^4$K
$\eta=10^{-6}$
$\tau_{ff}<\tau_{cool}$
$\tau_{ff}>\tau_{cool}$
no clouds
cloud dominant
1.0×10^{-4}
2.0×10^{-4}
5.0×10^{-4}
8.0×10^{-4}
1.0×10^{-3}
F_v
8
7
6
5
4
12
12.5
13
13.5
14
14.5
$\log R_h$ (pc)
$\log M_{total}(M_\odot)$



$T_c=10^4$K
$\eta=10^{-6}$
$F_v \times 10^4$
1.0
2.0
5.0
8.0
10
$M_{c,Jeans,p}$
allowed region
M_c
$F_v \times 10^4$
10
8.0
5.0
2.0
1.0
$\log M_c (M_\odot)$
$\log T_h$ (K)



$T_c=10^4$K
$\eta=10^{-6}$
$F_v \times 10^4$
1.0
2.0
5.0
8.0
10
$R_{c,crit}$
allowed
region
R_c
$F_v \times 10^4$
10
8.0
5.0
2.0
1.0
logR$_c$(pc)
logT$_h$ (K)